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SP-100 PROGRAM

Technical Information Report

SP-100 Attitude Control Pathfinder Study

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SP-100 ATTITUDE CONTROL PATHFINDER STUDY

F. O. Eke, S. H. Graff, R. A. Laskin, P. A. Swan

ABSTRACT

This report delineates the scope of Jet Propulsion Laboratory's FY'83 effort in the attitude control area in support of the SP-100 program. Dynamic modeling of the baseline beam configuration has been conducted and is presented herein. As a first cut, the beam is treated as rigid. Its inherent flexibility is then integrated via the hybrid coordinates method. Using the resulting dynamical equations, a preliminary look at attitude control is taken. Only one axis of rotation and one flexible mode are included. An alternative to the beam configuration is one that envisions connecting basebody to user via a long, lightweight, flexible tether. A literature search has been conducted in this area and the resulting bibliography is presented. The tether option is not considered viable near term. However, it offers several potentially significant advantages and thus deserves serious consideration for the next generation space power system.

This report also treats attitude control constraints imposed by the high temperature and radiation environment and addresses the issue of hardware requirements and availability.

Recommendations for FY'84 tasks include assembling and exercising a simulation program for the beam configuration dynamic model and conducting a technology assessment in the area of tether dynamics and control.

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I. INTRODUCTION

Abundant electrical power is a vital ingredient in our progress in space. This power is needed for large communication and navigation satellites, space stations, and exploration of the solar system.

The SP-100 nuclear space power system is nominally a 100 kW_e power source for applications which require high power and long life. The preliminary set of requirements calls for continuous power delivery for a period of seven years.

SP-100 requires an attitude control development to insure proper utilization of the current and future technology. Total integration of all the system components by JPL requires a design concept for each sub-system which can be used to compare, critique, and assess contractor inputs. The SP-100 challenges and opportunities for attitude control analysis include high reliability, high radiation levels, large temperature variations, long lifetimes, unusual vibrations from rotating and reciprocating machinery, and unique user requirements.

This study assessed the technology available for the baseline in the areas of articulation and deployment and dynamics and control of beams (with beam baseline of 25 meters), attitude control constraints, and finally the hardware commonality. An additional look at the concept of tethers, as a potential technology for the future, enables the program office to better assess the proposals of the contractors. The final conclusions and recommendations fill out the study with ideas and rationale for the future program office efforts.

II. BEAM DYNAMICS AND CONTROL

The SP-100 system may be visualized, as shown in Fig. 1, as two bodies B_1 and B_2 connected by a flexible truss B_3, and in orbit around the earth. B_1 is the power generating unit and may or may not be more massive than B_2. Depending on the precise type of power generation system adopted, B_1 may carry rotating or reciprocating machinery as well as working fluids.

The aim of the study reported here is to develop an acceptable mathematical model for the SP-100 system and to identify potential problems related to the attitude dynamics and control of the system.

II.A. Rigid Body Formulation

II.A.1 General Configuration

As a first step in the modeling of the SP-100, the system will be assumed to comprise two rigid bodies B_1 and B_2 connected by a rigid rod B_3, as shown in Fig. 1. m_i and $\underline{I}_i$ represent respectively the mass of body B_i, and the inertia dyadic of body B_i for its center of mass C_i.

The angular momentum of the system may be written as

$$\underline{H} = (\underline{I}_1+\underline{I}_2+\underline{I}_3) \cdot \underline{\omega} + \sum \; m_i\underline{r}_i \times (\underline{\omega}\times\underline{r}_i) \tag{1}$$

where $\underline{\omega}$ is the angular velocity of any of the bodies, and $\underline{r}_i$ is the position vector of C_i with respect to the center of mass C of the whole system. If one lets

$$\underline{I} = \underline{I}_1 + \underline{I}_2 + \underline{I}_3 \tag{2}$$

then

$$\underline{H} = \underline{I} \cdot \underline{\omega} + \sum \; m_i\underline{r}_i \times (\underline{\omega}\times\underline{r}_i) \tag{3}$$

and

$$\dot{\underline{H}} = \underline{I} \cdot \dot{\underline{\omega}} + \underline{\omega} \times \underline{I} \cdot \underline{\omega} + \sum \{m_i\underline{r}_i\times(\dot{\underline{\omega}}\times\underline{r}_i)+m_i\underline{r}_i\times[\underline{\omega}\times(\underline{\omega}\times\underline{r}_i)]\} \tag{4}$$

or

$$\dot{\underline{H}} = I \cdot \dot{\underline{\omega}} + \underline{\omega} \times I \cdot \underline{\omega} + \sum m_i\{-\underline{r}_i\times(\underline{r}_i\times\dot{\underline{\omega}})-\underline{\omega}\times[\underline{r}_i\times(\underline{r}_i\times\underline{\omega})]\} \tag{5}$$

If matrix formulation is desired, the unit vectors $\underline{e}_1$, $\underline{e}_2$, $\underline{e}_3$, are written as a vector array

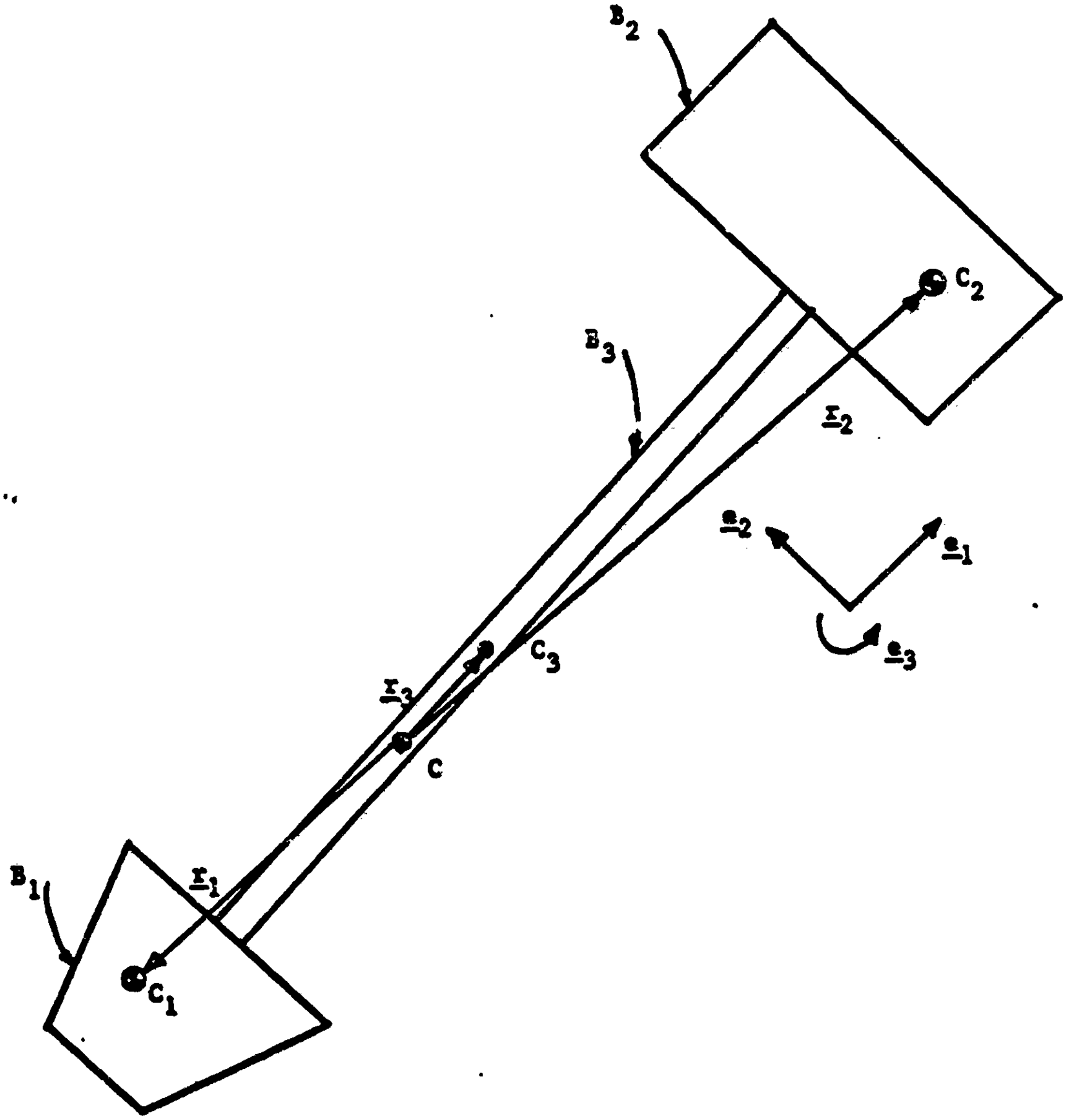


FIGURE 1: SP-100 System

$$\{e\} = \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} \tag{6}$$

and matrices $\dot{H}$, ω, r_i, and I_i are defined as follows:

$$\dot{\underline{H}} = \{e_x \; e_y \; e_z\} \begin{bmatrix} \dot{H}_x \\ \dot{H}_y \\ \dot{H}_z \end{bmatrix} = \{e\}^T\dot{H} \tag{7}$$

$$\underline{\omega} = \{e_x \; e_y \; e_z\} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \{e\}^T\omega \tag{8}$$

$$\underline{r}_i = \{e_x \; e_y \; e_z\} \begin{bmatrix} r_{ix} \\ r_{iy} \\ r_{iz} \end{bmatrix} = \{e\}^T r_i \tag{9}$$

and

$$I_i = \begin{bmatrix} I_{ix} & I_{ixy} & I_{ixz} \\ I_{ixy} & I_{iy} & I_{iyz} \\ I_{ixz} & I_{iyz} & I_{zz} \end{bmatrix} \tag{10}$$

The matrix equivalent of equation (5) then becomes

$$\dot{H} = I\dot{\omega} + \tilde{\omega}I\omega + \sum m_i \left(-\tilde{r}_i\tilde{r}_i\dot{\omega} - \tilde{\omega}\tilde{r}_i\tilde{r}_i\omega\right) \tag{11}$$

where the tilde (~) sign implies the cross operator; for example

$$\tilde{\omega} = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}$$

Defining

$$I_i' = I_i - m_i\tilde{r}_i\tilde{r}_i \tag{12}$$

and

$$I' = I_1' + I_2' + I_3' \tag{13}$$

Eq. (11) could be written in the more compact and familiar form

$$\dot{\underline{H}} = I'\dot{\omega} + \tilde{\omega}I'\omega = M \tag{14}$$

where M is a column vector whose elements are the components of the moment about the system mass center C of the resultant force on the system. Equation (14), supplemented with appropriate kinematical equations and control equations, may be used for the simulation of the motion of the system.

II.A.2 Symmetric Configuration

Real engineering systems of this type usually possess some amount of symmetry. In the specific case of SP-100, it is not unreasonable to assume, for example, that the axis of the rod B_3 passes through all mass centers, and that lines parallel to $\underline{e}_1$, $\underline{e}_2$, and $\underline{e}_3$ are centroidal principal axes for each of the bodies. The equations of motion in this case still have the form of equation (14), however, the expression for I' is much simpler. For three axis stabilized systems, like the SP-100, it is customary and reasonable to further assume that $\underline{\omega}$ is small so that the $\tilde{\omega} I' \omega$ term in equation (14) drops out, leading to the simple decoupled equations

$$\begin{aligned} \dot{\omega}_x &= M_x/I_x \\ \dot{\omega}_y &= M_y/I_y \\ \dot{\omega}_z &= M_z/I_z \end{aligned} \qquad (15)$$

II.B <u>Flexibility Considerations</u>

II.B.1 Model Description

Once the rigidity assumption of the previous section is discarded, one immediately runs into the difficulty of modeling a system which now includes a flexible beam between two rigid bodies. Several approaches to the analysis of flexible vehicles are treated in references [2] through [5]. When the ultimate aim is to arrive at equations of motion for computer simulation, the dynamical equations must be amenanable to a form (through appropriate coordinate transformation) that facilitates coordinate truncation so that system deformation may be represented by a finite number of "modal" coordinates.

The approach adopted in this study is the hybrid coordinate method of Likins [2]. This method is most useful when portions of an otherwise rigid vehicle undergo deformations that may be reasonably assumed to remain "small." For an efficient use of the above method, the SP-100 is modeled, as shown in Fig. 2, as a rigid body B_1 with a linearly elastic flexible appendage A. B_1 is taken to be the more massive of the two end masses of the real system, and the other end mass together with the flexible beam

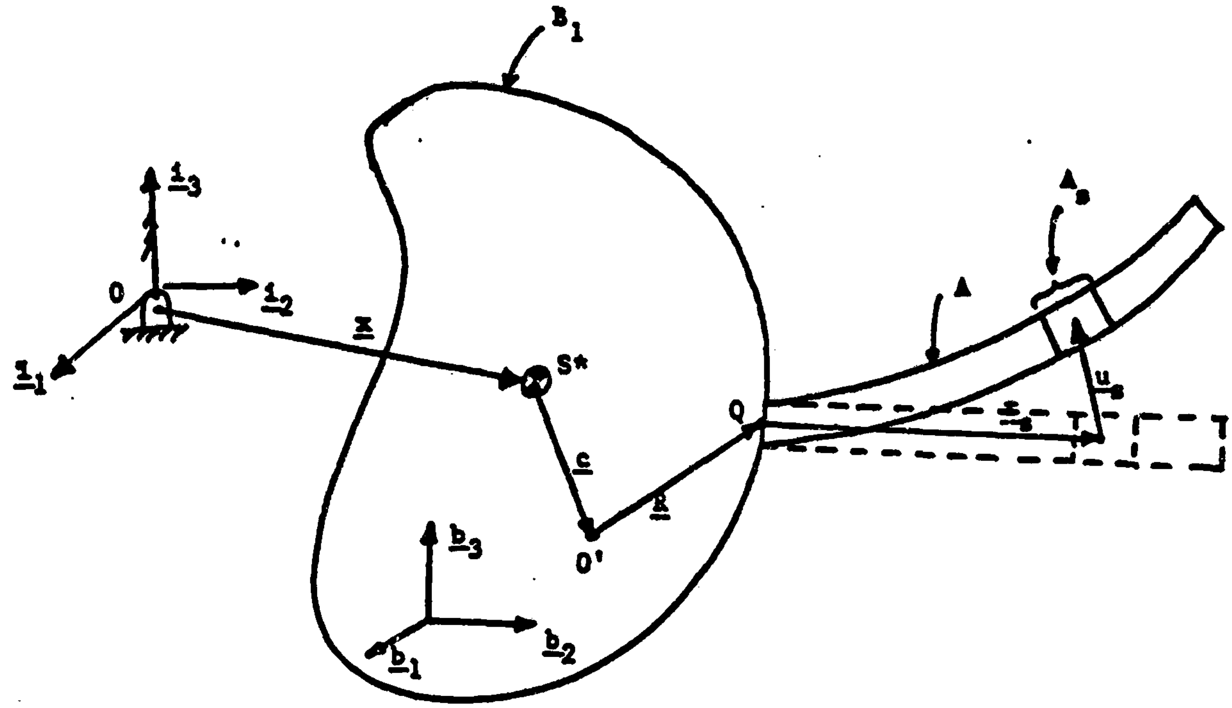


FIGURE 2: Flexible Beam Model

constitute the appendage A. Should B_2 be the larger mass, then it would be regarded as rigid and the remainder of the system considered as a flexible appendage. The next step is the derivation of equations of motion for the system just described, and this will be done by deriving the equations of motion for each appendage and then supplementing these with the equations of motion of the whole system viewed as a unit.

II.B.2 Appendage Equations

Consider the system in some general configuration depicted in Fig. 2. The appendage A undergoes "small" deformations relative to the base B_1, while the motion of B_1 is arbitrary. A is now idealized as a collection of n elastically interconnected discrete rigid sub-bodies, A_s being one such sub-body. Damping is ignored at this point; it wll be incorporated in the model at a later stage with the introduction of modal coordinates. The dotted lines in Fig. 2 show the position of A before deformation; point 0 is fixed in inertial space, S* is the system mass center, and 0' is the location of S* when the system was undeformed, and is therefore fixed in B_1.

For the sub-body A_s,

$$\underline{F}_s = m_s \ddot{\underline{p}}_s \tag{16}$$

where $\underline{F}_s$ is the resultant force on A_s, m_s is its mass, and $\underline{p}_s$ is the position vector of the center of mass of A_s relative to 0. On the other hand, it is clear from the figure that

$$\underline{p}_s = \underline{X} + \underline{C} + \underline{R} + \underline{r}_s + \underline{u}_s \tag{17}$$

where

$\underline{X}$ is the vector from 0 to S*

$\underline{C}$ is the position vector of 0' relative to S*

$\underline{R}$ is the vector from 0' to a point Q fixed in B_1

$\underline{r}_s$ vector goes from Q to the location of the mass center of A_s in the undeformed configuration, and

$\underline{u}_s$ is the position vector of the mass center of A_s relative to its location in the undeformed configuration.

Hence

$$\underline{F}_s = m_s(\ddot{\underline{X}} + \ddot{\underline{C}} + \ddot{\underline{R}} + \ddot{\underline{r}}_s + \ddot{\underline{u}}_s) \tag{18}$$

Column matrices X, C, R, r_s, and u_s are now defined as follows

$$\underline{X} = \{\underline{i}_1\ \underline{i}_2\ \underline{i}_3\} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} = \{\underline{i}\}^T X \tag{19}$$

$$\underline{C} = \{\underline{b}_1\ \underline{b}_2\ \underline{b}_3\} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} = \{\underline{b}\}^T C \tag{20}$$

$$\underline{R} = \{\underline{b}_1\ \underline{b}_2\ \underline{b}_3\} \begin{bmatrix} R_1 \\ R_2 \\ R_3 \end{bmatrix} = \{\underline{b}\}^T R \tag{21}$$

$$\underline{r}_s = \{\underline{b}_1\ \underline{b}_2\ \underline{b}_3\} \begin{bmatrix} r_{s1} \\ r_{s2} \\ r_{s3} \end{bmatrix} = \{\underline{b}\}^T r_s \tag{22}$$

$$\underline{u}_s = \{\underline{b}_1\ \underline{b}_2\ \underline{b}_3\} \begin{bmatrix} u_{s1} \\ u_{s2} \\ u_{s3} \end{bmatrix} = \{\underline{b}\}^T u_s \tag{23}$$

It then becomes possible to write Eq. 18 in matrix form as

$$F_s = m_s\ [\text{Ⓗ}\ddot{X}+\ddot{C}+2\tilde{\omega}\dot{C}+\tilde{\omega}\tilde{\omega}(C+R)-(\tilde{C}+\tilde{R})\dot{\omega}-(\tilde{r}_s+\tilde{u}_s)\dot{\omega}+\tilde{\omega}\tilde{\omega}(r_s+u_s)$$
$$+2\tilde{\omega}\dot{u}_s+\ddot{u}_s] \tag{24}$$

where Ⓗ is the transformation matrix between the $\underline{i}$ and $\underline{b}$ bases given by

$$\{\underline{i}\}^T = \{\underline{b}\}^T \text{Ⓗ} \tag{25}$$

The matrix C represents the motion of the system mass center in B_1, and may be shown to be given by

$$C = -\sum \mu_s u_s \tag{27}$$

where $\quad \mu_s = m_s/(\sum m_s) \qquad (28)$

Equation (27) and its time derivatives may be substituted into equation (24) to give

$$F_s = m_s[\text{Ⓗ}\ddot{X} + \ddot{u}_s - \sum \mu_k\ddot{u}_k + 2\tilde{\omega}(\dot{u}_s - \sum \mu_k\dot{u}_k) - (\tilde{R}+\tilde{r}_s)\dot{\omega} + \tilde{\omega}(u_s - \sum \mu_k u_k)$$
$$+ \tilde{\omega}\tilde{\omega}(R+r_s+u_s-\sum \mu_k u_k)] \tag{29}$$

The equations of rotational motion of A_s are obtained by equating the resultant external torque on A_s to the time rate of change of its inertial angular momentum. Since the rotation of A_s relative to B_1 is due only to "small" structural deformations, this rotation can be represented by the vector

$$\underline{\beta}_s = \beta_{s1}\underline{b}_1 + \beta_{s2}\underline{b}_2 + \beta_{s3}\underline{b}_3 \tag{30}$$

where β_{s1}, β_{s2}, β_{s3} are three angles of rotation about the orthogonal axes $\underline{b}_1$, $\underline{b}_2$, $\underline{b}_3$. Hence, the angular velocity matrix ω_s of A_s takes the form

$$\omega_s = \omega + \{\underline{b}\}^T \dot{\beta}_s \tag{31}$$

Finally, the equations of attitude motion of A_s can be put in the form

$$T_s = I_s(\dot{\omega}+\ddot{\beta}_s) + [I_s\tilde{\omega}+\tilde{\omega}I_s-\widetilde{(I_s\omega)}]\dot{\beta}_s+\tilde{\omega}I_s\omega + [I_s\tilde{\dot{\omega}}-\widetilde{(I_s\dot{\omega})}-\tilde{\omega}\widetilde{(I_s\omega)}+\tilde{\omega}I_s\tilde{\omega}]\beta_s \tag{32}$$

where

T_s is the resultant torque matrix

and I_s is the centroidal inertia matrix of A_s.

For a three-axis stabilized system, equations (29) and (32) may be linearized in ω, they then reduce respectively to

$$m_s(\ddot{u}_s - \sum \mu_k\ddot{u}_k) = -m_s Ⓗ \ddot{X} + (\tilde{R}+\tilde{r}_s)\dot{\omega} + F_s \tag{33}$$

and

$$I_s\ddot{\beta}_s = -I_s\dot{\omega} + T_s \tag{34}$$

II.B.3 Vehicle Equations

Equations (33) and (34) are not sufficient for the complete description of the motions of our system. They will now be supplemented with the dynamical equations of the whole vehicle.

The vehicle translational equation is

$$\underline{F} = m\underline{a}^{s*} \tag{35}$$

where F is the resultant external force on the whole vehicle, m is the total mass, and $\underline{a}^{s*}$ is the acceleration of the system mass center. The matrix form of equation (35) is

$$F = m Ⓗ \ddot{X} \tag{36}$$

and the rotational equations for small ω can be written in the compact form

$$T = I^*\dot{\omega} + R\sum m_s\ddot{u}_s + \sum \tilde{r}_s m_s\ddot{u}_s + \sum I_s\ddot{\beta}_s \tag{37}$$

where I^* is the inertia matrix of the undeformed vehicle for the point 0′ of Figure 3. A comparison of Equations (15) and (37) indicates that the effects of beam flexibility are contained in the last three terms on the right hand side of Equation (37). Equations (33), (34), (36), and (37) form a set of 6n+6 scalar equations with X, Ⓗ, ω, u_s and β_s (6n+9 in number) as unknowns. And together with a set of kinematical equations relating Ⓗ and ω, and control equations, they are sufficient for the simulation of the motions of the system.

II.B.4 Modal Truncation

The difficulty with the equations mentioned above is simply their dimension due mainly to the appendage equations whose number is directly proportional to n. The objective in this subsection is to attempt a reduction of the dimension of the equations of motion through some type of coordinate truncation. This naturally involves the introduction of a linear transformation for at least some of the variables, and this transformation must give rise to decoupled equations so as to permit valid truncation. Here, such a transformation is applied to the appendage deformation coordinates only. First, the appendage deformation coordinates are organized into a coordinate matrix q defined as

$$q = [u_1^1 \; u_2^1 \; u_3^1 \; \beta_1^1 \; \beta_2^1 \; \beta_3^1 \; u_1^2 \; u_2^2 \; u_3^2 \; \beta_1^2 \; \beta_2^2 \; \beta_3^2 \; \ldots \; \beta_3^n]^T \tag{38}$$

Because the appendage equations (33) and (34) are linearized in the deformation coordinates u_s and β_s, these equations can be written in matrix form as

$$M'\ddot{q} + D'\dot{q} + K'q = L' \tag{39}$$

By inspection of equations (33) and (34), it becomes evident that M' is a constant symmetric matrix. F_s and T_s in equations (33) and (34) include structural interaction forces and torques between neighboring sub-bodies of A. These interactions may be visualized as linearly elastic and viscous forces and torques that are proportional to the deformation and deformation rates. Hence D' and K' are also constant matrices; all the damping coefficients go into D' and all the stiffnesses go into K'. L' depends on $\oplus$, $\ddot{X}$, and the external applied forces and torques that may appear in F_s and T_s.

Classical modal analysis techniques can be applied to our system by first ignoring damping and considering

$$M'\ddot{q} + K'q = L' \tag{40}$$

This leads to the choice of the normal-mode transformation

$$q = \phi\eta \tag{41}$$

which in turn transforms equation (39) into

$$\ddot{\eta} + 2\zeta\sigma\dot{\eta} + \sigma^2\eta = \phi^T L' \tag{42}$$

where η is the column matrix of modal coordinates, σ and ζ are diagonal matrices of natural frequencies and damping ratio, and ϕ is the modal matrix.

Equations (42) are now decoupled and may be truncated to a convenient size. If $\bar{\eta}$ is the truncated form of η, the appendage equations now take the form

$$\ddot{\bar{\eta}} + 2\zeta\dot{\bar{\eta}} + \sigma^2\bar{\eta} = \phi^T L' \tag{43}$$

Depending on the number of "modes" retained, this truncated form of the appendage equations, together with the vehicle equations could constitute a much smaller set of dynamical equations, and therefore much cheaper to integrate on a computer.

II.C <u>Effects of Rotating and/or Reciprocating Machinery</u>

II.C.1 Rigid Formulation

The addition of a rotating element to one of the main bodies of the system introduces a slight change in the equations of attitude motion. For example, let us examine the case of Fig. 1 where the connecting rod between B_1 and B_2 is assumed to be rigid, and body B_1 contains a rotor. If this added rotor is axisymmetric, then B_1 is a gyrostat and the system angular momentum is augmented by a term h which represents the angular momentum of the rotor relative to the basebody B_1. Equation (15) then has the matrix form

$$T = I\dot{\omega} + \dot{h} - \tilde{h}\omega \tag{44}$$

which now includes a "gyroscopic stiffness" term. Hence, the motion of an axisymmetric rotor in B_1 does affect vehicle motion. The importance of this effect depends on the inertia of the rotor, and its spin rate relative to the basebody B_1. If the rotor mass center is offset from the spin axis, the system's dynamics is further complicated by the appearance of new terms involving this offset.

II.C.2 Flexible Body Formulation

In the case of a flexible beam, the presence of a rotor on body B_1 can affect both the appendage equations and the vehicle equations. The appendage equations can only be affected through the column vector C (see Eq. (24)) which represents the motion of the system mass center in body B_1. If the rotor is axisymmetric, then the location of the system mass center is not modified by the motion of the rotor, and hence, the appendage equations remain unchanged. This means that the procedure and results of the coordinate matrix truncation are unaffected by the motion of a symmetric rotor in B_1. However, the vehicle equations change slightly because the expression for the angular momentum of the system is modified by the presence of the rotor. The vehicle equation of rotational motion becomes

$$T = I^*\dot{\omega} + \dot{h} - \tilde{h}\omega + \tilde{R}\sum m_s\ddot{u}_s + \sum I_s\ddot{\beta}_s + \sum \tilde{r}_s m_s \ddot{u}_s \qquad (45)$$

The first term on the right hand side of Eq. (45) is the rigid body term. It is the only term that would remain if the whole system were one rigid body. The second and third terms are due to the presence of the rotor, and the last three terms are contributions from the system's flexibility.

If the rotor mass center is not located on the spin axis, the rotor's motion will affect the location of the system mass center. That is, the appendage equations will be impacted through the C matrix, and the modal analysis technique used above breaks down because D' and K' are no longer constant matrices.

II.D Control System

Since our system is three-axis stabilized, the elements of the matrix ω are small, and we can let

$$\omega = \dot{\theta} \qquad (46)$$

where $\quad \theta = [\theta_1\ \theta_2\ \theta_3]^T \qquad (47)$

and θ_1, θ_2, θ_3 are vehicle rotation angles. If our interest, from controls point of view, is limited to θ, it will be necessary to display clearly the relationship between the control torque T and the rotation angle θ. As a simple example, we consider the case of negligible external force and torque on the appendage. System equations may then be reduced to

$$T = I^*\ddot{\theta} - \delta^T\ddot{\eta} \qquad (48)$$

and $\ddot{\eta} + 2\zeta\sigma\dot{\eta} + \sigma^2\eta = \delta\ddot{\theta} \qquad (49)$

The Laplace transform of these equations yields

$$T(s) = s^2 I^*\theta(s) - \delta^T s^2 \eta(s) \qquad (50)$$

and $\quad s^2\eta(s) + 2s\zeta\sigma\eta(s) + \sigma^2\eta(s) = s^2\delta\theta(s) \qquad (51)$

Equations (50) and (51) can be combined to give

$$\theta(s) = [sI^* - s^4\delta^T D\delta]^{-1} T(s) \qquad (52)$$

where D is a diagonal matrix given by

$$D = \begin{bmatrix} \frac{1}{s^2+2\zeta_1\sigma_1 s+\sigma_1^2} & & 0 \\ & \frac{1}{s^2+2\zeta_2\sigma_2 s+\sigma_2^2} & \\ 0 & & \frac{1}{s^2+2\zeta_N\sigma_N s+\sigma_N^2} \end{bmatrix} \tag{53}$$

In the special case when the coordinate truncation is carried down to a single modal coordinate, Eq. (52) becomes

$$\Theta(s) = \frac{1}{s^2}\left[I^* - s^2\delta^{1T}\delta^1 \left(\frac{1}{s^2+2\zeta\ \sigma\ s+\sigma^2}\right)\right]^{-1} T(s) \tag{54}$$

A block diagram representation of this control system is shown in Fig. 3. If it is further assumed that dynamic response in this single mode representation influences vehicle response about one axis only, and that the inertia matrix I^* is diagonal, then the dynamics block of Fig. 3 can be expressed as

$$G(s) = \left[I_\alpha^* s - \frac{s^4(\delta_\alpha^1)^2}{(s^2+2\zeta_1\sigma_1 s+\sigma_1^2)}\right]^{-1} \tag{55}$$

where α is the single axis considered. This expression can eventually be put in the form

$$G(s) = \frac{s^2+2\zeta_1\sigma_1 s+\sigma_1^2}{I_\alpha^* s^2(s^2E+2\zeta_1\sigma_1 s+\sigma_1^2)} \tag{56}$$

where $$E = 1 - \frac{(\delta_\alpha^1)^2}{I_\alpha^*} \tag{57}$$

In the case of simple gain control,

$$H(s) = K \text{ (constant)} \tag{58}$$

and the characteristic equation becomes

$$s^4(I_\alpha^* E) + s^3(2I_\alpha^*\zeta_1\sigma_1) + s^2(I_\alpha^*\sigma_1^2+K) + s(2K\zeta_1\sigma_1) + K\sigma_1^2 = 0$$

An examination of the Routhian array for this system indicates asymptotic stability for positive K.

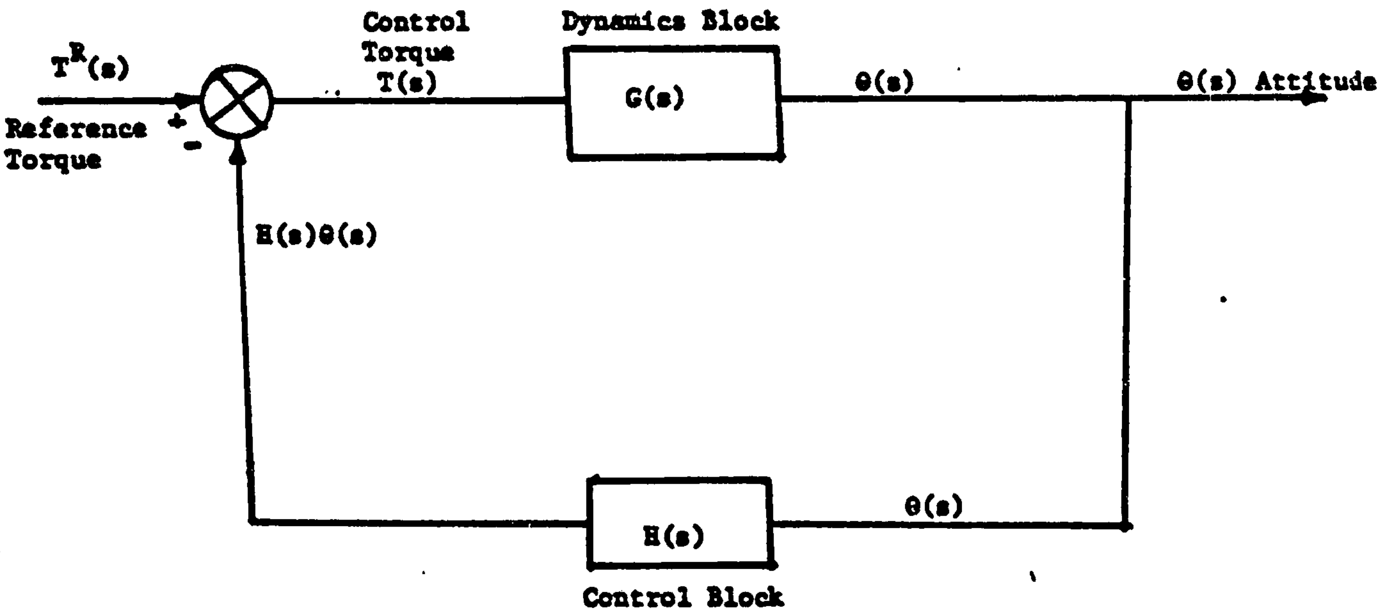


FIGURE 3: Block Diagram

II.E Findings

The formulation of equations of motion for the SP-100 system could be described as complete. If the connecting structure of the system is assumed to be rigid, the equations of motion are very simple and decoupled. When the flexibility of the structure is taken into account, the system is modeled as a main rigid body with an attached flexible appendage, the other rigid body being assimilated into the appendage. Furthermore, the appendage is modeled as a system of elastically interconnected rigid sub-bodies. The complete dynamical equations of the system are then composed of the appendage equations together with the complete vehicle equations. Truncation of these equations is achieved through modal analysis of the appendage equations. These reduced dynamical equations can then be completed with kinematical and control equations for the purposes of vehicle motion simulation.

When the basebody contains a perfectly axisymmetric rotating or reciprocating sub-body, the effects of the motion of such a rotor are easily accommodated in the analyses presented because they are decoupled from flexibility effects.

A preliminary analysis of the control system using the extreme example of single axis response of an appendage represented by a single modal coordinate, with simple gain control, reveals asymptotic stability in every case.

III. TETHER CONFIGURATION

The SP-100 program has two major areas for potential benefit and two areas of smaller potential for future utilization of tether technology. The major aspects of tether technology that apply to SP-100 are 1) radiation attenuation and 2) disturbance isolation. The two ancillary aspects of the tether technology are 1) the ability to provide gravitational fields and 2) the adjustment capability for attitude control without the use of propellants. These benefits will be discussed further. The concept of tethers and their applications in space have recently identified potential applications to both Earth and interplanetary missions. Notably, tethers can provide unique techniques for scientific measurements. By using a constellation of tethered satellites, simultaneous sampling and multiple measurements of electromagnetic and atmospheric characteristics at stereographic observations, sample retrieval of low altitude atmospheric gases of a planet, such as Jupiter, or a fly-by comet can be easily accomplished across multiple locations. Tethers also provide the option of using less fuel for maneuvers such as spacecraft insertion, orbit adjust, and science probe injection towards planets.

Extensive work has been done in the dynamics and control of space vehicles; however, the addition of long (in excess of 80 km) tethers creates new and unusual aspects to the calculations. The initial efforts by NASA in the early days of Gemini studied the dynamics and control of short tethers (order of 100 m) to provide gravity gradient stabilization and spin induced gravity. These activities were accomplished both in orbit and in simulations. Recent efforts have surfaced with emphasis on the uses of long tethers mainly due to the better understanding of the dynamics pioneered by Professor Colombo of the Smithsonian Astrophysical Observatory. These efforts have initiated interest in many universities and laboratories to better understand the simulations. The recent emphasis has centered around the new missions that have become better understood since the new dynamical modeling has been discussed in the literature.

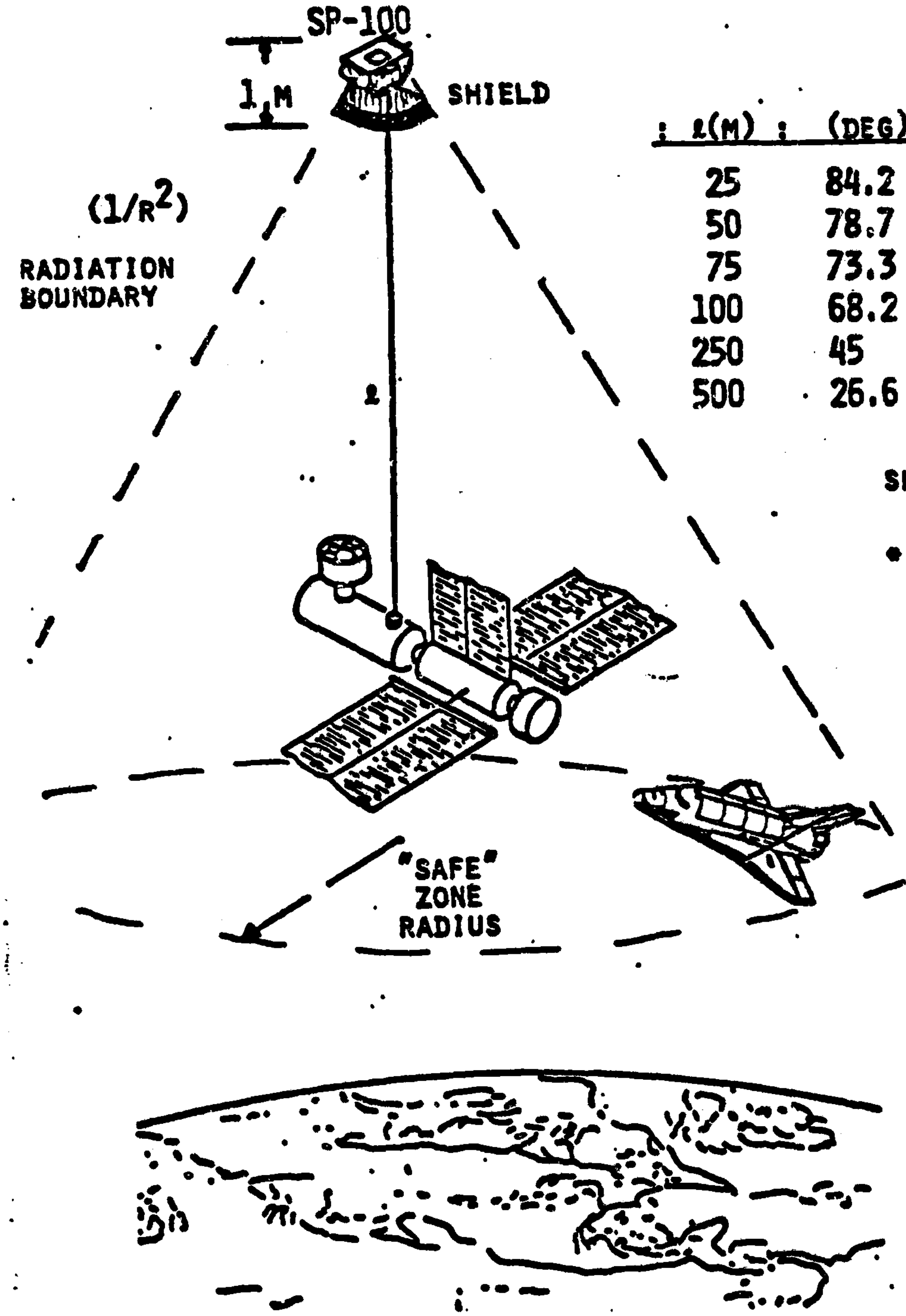
Currently, NASA is pushing the concepts of tethers that relate to the Earth resources or Earth oriented activities. The new ideas of gravity gradient induced gravitational forces for manned activities (about .1 g's), of "free" altitude additions from "spare" masses provided to the shuttle orbits, and of scientific measurements in the upper atmosphere from medium orbits of the orbiters have created much interest in the earth resources and space sciences community.

Two joint U.S.-Italian missions scheduled for 1987 and 1988 will demonstrate the feasibility and benefits of tethered satellite systems deployed from the shuttle orbiter. The tether will be a flexible metallic or synthetic line, 1-2 mm in diameter and 100 Km or more in length, carrying a total payload mass of 500 Kg. Because of the differences in environmental parameters at the outer planets, (such as gravity and aerodrag) the requirements and characteristics of tethers will vary from the above Earth oriented missions. Furthermore, current work on tether dynamics and controls are relatively immature. It is timely now to verify the tether concept for applications to future planetary, earth resources, and military missions.

Several representatives of the SP-100 project attended the NASA sponsored Tether Workshop in Williamsburg, Virginia in June 1983. Their participation in the Tethers Workshop resulted in a better understanding of the current technology and programmatic paths. The emphasis was related to Earth oriented activities and rarely investigated the possibilities of interplanetary activities. A major conclusion from this Tether Workshop was that the modeling of the dynamics and control of orbiting tethers must be investigated thoroughly. The current models vary in assumptions, in structure, and sometimes in conclusions.

The support of SP-100 conducted a basic reference research effort with the compiling of many articles and books pertaining to tether systems (see attached bibliography). The initial assessment of the dynamics and control of tether satellite systems has shown that there are four potential benefits.

(a) Radiation Attenuation: Figure 4 shows a generic case of a nuclear power system with the length of the tether varying from 25 meters (baseline) to 500 meters. This increase in distance (r) decreases the amount of



ℓ(M)	θ (DEG)*	SHIELD RADIUS (M)	SHIELD AREA (M^2)
25	84.2	10	314
50	78.7	5	78.5
75	73.3	3.3	34.9
100	68.2	2.5	19.6
250	45	1.0	3.14
500	26.6	.5	.79

SHIELD AREA ∝ MASS

* θ's FOR 500 METER DIAMETER "SAFE" ZONE

FIGURE 4: Tether Radiation Attenuation

shield area to protect a satellite safety zone by a rate of $1/r^2$. A tether on the order of 10 km might render shielding totally unnecessary.

(b) Vibration Isolation: A tether system will provide the ability to attenuate vibrations through the use of a tether with no (very small) transmission of shear forces. This provides a protection from vibration that must be studied to quantify the effect.

(c) Gravity Field: The stable tether system will rotate once during each orbit. This slow rotation and long tether length (moment arm) will provide a small amount of artificial gravity through centrifigual force. This could have significant safety implications for the reactor.

(d) Attitude Adjustment: By placing the center of mass around the attachment point, fine adjustments can be achieved of the attitude of the satellite. This can be accomplished with electromechanical devices instead of costly propellant usage.

IV. COMMONALITY

Several attitude control constraints and hardware uses are common to the two configurations. The SP-100 attitude control subsystem has both temperature and radiation constraints. The radiation limit for the Galileo project which is 5×10^9 protons/cm^2 and 1×10^6 neutrons/cm^2 with design margin of 2, was selected for the electronics. Off-the-shelf electromechanical devices such as resolvers reaction wheels, gyros and motors have a limit of 250 to 500 krads due to lubrication and insulation breakdown. These electromotive devices can be designed for even higher radiation levels. Presently, sun sensors can tolerate up to 150 krads, however, star sensors are not radiation hardened and therefore present a problem. Earth sensors radiation hardened to greater than 500 krad are currently available.

When the reactor is operational the radiator temperature may be as high as 900° K. When the reactor is shut down, the electronics will need heaters. The electronics temperature range which has been selected for now is the same as for the Galileo Project which is from 273° to 328° K with qualification limits at 253° to 348°K.

The extreme temperature range leads to consideration of heaters and insulation for the propulsion system. The Jet Propulsion Laboratory's limits for Hydrazine with Shell 405 catalyst are from 275° K to 322° K, although an upper limit 340°K is possible. This yields an I_{SP} of 233 seconds at 300 psai for an expansion ratio of 50. To prevent propellant line freezing, line heaters are required. Viking and Galileo Projects selected dinitrogen tetroxide (NTO) and monomethyl hydrazine (MMH) which has a temperature range from 221° K to 361° K with an I_{SP} of 349 seconds at 140 psia for an expansion ratio of 40. Unfortunately, unburned NTO and MMH leaves solid particle residue. Clorine pentafloride (CPF) and MMH has a temperature range from 221° K to 338° K with an I_{SP} of 363 seconds at 150 psia for an expansion ratio of 40. For a lower freezing point with Mixed Hydrazine Fuel 3 (MHF-3) which has a range from 208° K to 338° K and an I_{SP} of 342.1 seconds at 150 psia and an expansion ratio of 40. CPF has a higher I_{SP}, higher density, lower freezing point (170° K), higher combustion efficiency and lower plume contamination then Hydrazine or NTO and MMH. The CPF technology is widely available and it has been burned in test bed engines at the Air Force Rocket Propulsion Laboratory, Rocketdyne, Aerojet General, Thiokol Reaction Motors, TRW, and the Jet Propulsion Laboratory. While CPF is corrosive, it has been stored for up to ten years safely. Therefore CPF with MMH or MHF-3 has been recommended for SP-100.

The potential of propellant line freezing combined with the propellant line deployment has led to the decision that each subsatellite, whether deployed by a beam or tether, should have its own set of propellant tanks and lines with one attitude control system for the thrusters.

To reduce the high temperature and high radiation impacts on the user's subsystem the user will be remote from the reactors. This led to the beam and tether configurations, both of which require various sensors and actuators to handle the attitude control considerations.

Since large amounts of electrical power are available, attitude control should emphasize reaction wheels, control moment gyros, magnetic torquers, rather than thrusters as primary devices. Table 1 shows the possible primary effectors and sensors for various mission orbits and trajectories. Magnetic torquers and gravity gradient are viable contenders for the primary system only in low planetary orbits. The exact choice of effectors and sensors depends on mission requirements and further investigation of the SP-100 design.

TABLE 1: Control Implementation

	LOW ORBIT	HIGH ORBIT	HIGHLY ELLIPTICAL ORBIT	INTERPLANETARY
THRUSTERS	X	X	X	X
GRAVITY GRADIENT	X			
MAGNETIC TORQUERS	X			
CONTROL MOMENT GYRO	X	X	X	X
REACTION WHEEL	X	X	X	X
MOMENTUM WHEEL	X	X	X	X
SUN SENSOR	X	X	X	X
STAR SENSOR	X	X	X	X
EARTH SENSOR	X	X	X	X

V. CONCLUSION

The deployable beam configuration uses an off-the-shelf item with a 20:1 expansion ratio. Thus a 24 meter beam uses slightly more than one meter of shuttle cargo bay length. The dynamics are well understood, although the power and AACS cable deployment with the beam is a concern. This is a good conservative approach for today.

Tethers offer a low radiation user environment and vibration isolation. There are many advantages for applications of tethers which are harder to achieve with the beam configuration: radiation isolation, artificial gravity, and vibration isolation are three. While tether materials and fabrication needs further study, this is a good approach for future space power applications. Tethers should not be proposed as the baseline system at the present time; however, the study effort should continue to insure that the benefits could be incorporated if they fulfill their potential.

The attitude control pathfinder study is a good start, but without adequate mission requirements or tools, the design options cannot be fully assessed. Therefore, the following is recommended:

In the beam dynamics area, the dynamics model should be put into a computer simulation. Further, modeling and subsequent incorporation into the simulation program is required to quantify:

1. the effects of fluid motion in the basebody on the dynamic behavior of the system;
2. the effects of rotating or reciprocating machinery in the base body, particularly when the rotating body is <u>non-axisymmetric</u>. This may lead to a strong coupling between the motion of the rotor and appendage deformations.

The controls work presented in this report is very preliminary in the sense that the final results were restricted to a single mode representation and a single axis control. A generalization to several modes and three axes control is needed. Furthermore, a decision on the exact location of sensors and effectors in the light of the existing constraints still has to be made; and this will have an impact on the final form of the control equations.

In the tether area, using the extensive bibliography, tether dynamics and controls should be investigated further at JPL with an eye toward application to the next generation SP-100.

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